A strategy for development of hydrogen technologies in Denmark

Final report from the committee on economy and perspectivescommissioned by the Danish Energy Agency

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[¤] CR was prevented by other assignments to take part in the work and has not commented on the several draft versions of the present report produced over the past three months. OB has been alternating with HØP and AHP has been replacing AM during travel periods.

List of contents

Terms of reference:

The committee is asked to describe economic and social perspectives related to hydrogen technology development, using a high-level, integrated approach and emphasising the opportunities for Danish contributions. The basis for the work should be the previous hydrogen scenario report (ref. 29) and a view to the ongoing 2025 action planning. The emerging findings of the parallel work by 4 specific hydrogen technology groups and the group on international collaboration should be incorporated. Recommendations should be made for economical and political measures aimed at enhancing the development of hydrogen technologies for use in the energy supply chains of both the stationary and the transportation energy sectors.

(English rendering of memorandum 31013-0004 committee-6 text from Danish Energy Agency, 15.06.2004)

Summary of recommendations for R&D and for market stimulation

Based on the technology assessment and potential price developments described in sections 1-6, the implications for Danish energy policies outlined in section 7, and the Danish areas of competence identified in section 8, a set of recommendations has been formulated in section 9. The funding recommendations should be seen as having a horizon of about 5 years. The recommendations for hydrogen production, storage and applications are listed here in tabular form and with no ranking intent in the choice of sequence:

Activity area where support is recommended	*Research at basic and applied science levels*	*Industrial development & initial market stimulation*
Small conventional fuel to hydrogen reformers: improving efficiency, reliability and reducing price		Development primarily based on industry funding
Reversible PEM (proton exchange membrane) fuel cells (for distributed or central use), getting electrolysis efficiencies above 90%	Basic process understanding, prototyping	Optimising design
Reversible (or just reversed operation) SOFCs (solid oxide fuel cells), electrolysis efficiency above 90%	Basic science, experiments	
Salt intrusion and aquifer hydrogen storage	Modelling and diffusion measurements	Reduced scale integrity tests
Hydride and other advanced hydrogen storage	Laboratory optimisation	Design
PEM fuel cells for stationary or mobile applications	Modelling, optimisation	Increasing reliability, durability, decreasing cost
PEM-like acid fuel cells operating at 150-200°C	Basic process understanding, prototyping	
Fuel cell system components such as controls		Intelligent package design
Fuel cell systems and integration, with current focus on CPH (combined power & heat) and UPS (uninterruptible power supply)	Ideas for new systems and applications	Reliable and competitive designs
SOFCs and systems	Modelling, optimisation	Increasing reliability, durability, decreasing cost
Scenario studies	Providing policy alternatives	
Environmental assessments	For components and systems	
Sustainable transportation and renewable energy (general recommendation, not just for hydrogen)	Establish permanent research units	

1. Introduction

The basis for the interest in hydrogen technologies in Denmark has two components:

• The introduction of renewable energy sources has been quite successful in Denmark. Only the transportation sector has not yet been amenable to renewable energy introduction, although research on certain biofuels have provided hopes. Hydrogen is one alternative fuel for automotive applications, and the emphasis placed upon it by the international automobile manufacturing industry makes it an obvious candidate also for the Danish transportation sector (which cannot act independently from the international decisions made in this area). However, Denmark can ensure that the technology for producing hydrogen from renewable sources such as excess wind power is developed.

• The already substantial and increasing use of wind power entails a fluctuating power production not matching demand on the shorter time-scales (weeks and below). Hydrogen as a storable fuel-type energy is seen as one of the most promising storage technologies for applications with bulk energy storage requirements of up to several weeks. Despite existing availability of international grid trading connections and possibly in the future demand management, these methods are less suitable than hydrogen production for handling very large quantities of power surpluses arising with short warning times.

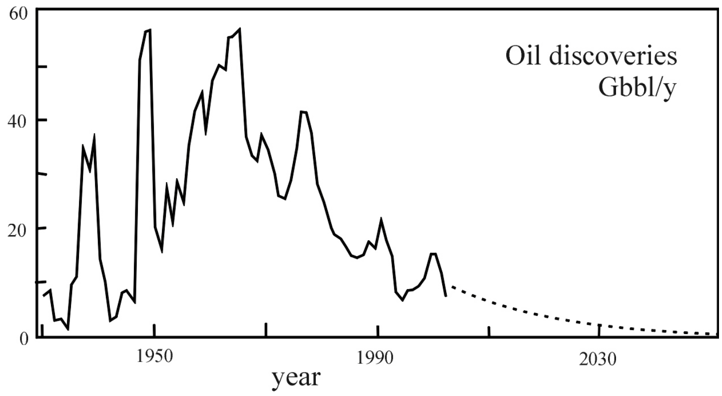

Figure 1. Year-by-year global oil discoveries and the results of a model for future finds. Based on (47, 48).

1.1 Background

The time-frame for the necessary changes in the energy system and thus the urgency of the R&D initiatives related to hydrogen, is illustrated by the prospects for continued reliance on oil and expectations of oil price developments. Figure 1 shows the decline in finding new exploitable oil fields. The energy contents of new finds topped before 1970, and in contrast to the erratic exploration efforts prior to 1950, the subsequent global efforts have been much more systematic and hence the probability of unexpected large finds in the future is considered low. Enhanced recovery techniques beyond the gas injection method already in widespread use could lead to an upgrading of existing reserve estimates. However, the proposed methods (such as *in situ* combustion, using bacteria to release oil from rock pores, high-pressure chemistry) do not have universal applicability and can at best release some 20% of the 60% of oil resources presently left trapped in the geological formations (cf. ref. 52). High investment costs are associated with increasing production above the present level, whether using new enhanced recovery methods or exploiting new reservoirs, such as Canadian tar sands or Venezuelan shales.

Figure 2 gives some model results for the near-term development of oil production and oil prices. On the basis of the data shown in Figure 1 and the remarks on unconventional oil recovery techniques, it is assumed that half of the exploitable reserves have been used by 2010. The uncertainty of this estimate is low (of the order of ±10 years, unless quite unexpected new oil finds materialise) and is supported by many international investigations (48, 54). However, the fact that we are at the mid-point of reserves does not determine the rate of oil use during the next decades. High use will be followed by a more abrupt decline, and price excursions are likely to increase. Figure 2 shows the behaviour in 3 models, assuming that oil production is growing (a), is constant (b) or declines symmetrically with its historical growth (c). The latter possibility, the Hubbert bell shaped curve (51), is unlikely because it assumes readily available substitution of oil by other energy forms at similar prices. Case (b) of staying at current oil production level requires a partial substitution to be available for covering the demand growth. Candidates such as liquefaction of coal or biomass into oil-substituting fuels currently have price tags equivalent to around 100 US$/bbl of oil or higher, which is reflected in the lower part of Figure 2. In this case, reserves will be exhausted around 2043 (consistent with ref. 45). Finally case (a) assumes that production is increased to cater to the new consumer countries (China, India, etc.). Its 25% increase in oil usage from 2004 to 2030 assumes a 30% increase in world car ownership over the next 25 years, an assumption that few will find exaggerated. The reserves now last only to around year 2038. A recent IEA report (53) has an even higher 60% increase in energy use to 2030 in its reference scenario. The implication of such scenarios is a 60% increase in CO_2 emissions (53) and a 60% increase in OPEC oil production, while non-OPEC oil production will decline during the period (54).

The geopolitical and supply-security implications of this development are huge. Both IEA and the Center for Strategic & International Studies (CSIS) in Washington DC recommend energy policies reducing demand and speeding up a transition away from oil dependence. They differ in that IEA believes that increasing the oil production sufficiently is possible at least to 2030, while the CSIS predicts a demand-supply gap already during the period 2014-2020, for a corresponding global demand growth varying from 2.4 to 1.1% per year. A recent study by the oil industry supports the CSIS view (55), while the analysis in Figure 2 is also consistent with IEA, by setting year 2038 as the limit for covering demand by increased oil production. In all cases, the price of oil is predicted to go up substantially. In the high production scenarios, the sudden onset of decline in supply is likely preceded by crisis conditions that could have been avoided by a planned winding-down of production. Short-term behaviour of the oil price is likely to exhibit the fluctuations characteristic for a nervous and hypersensitive market, perhaps including price decreases below the current one. However, the solidity of the reasoning behind expecting a phase-out of conventional cheaply produced oil is high.

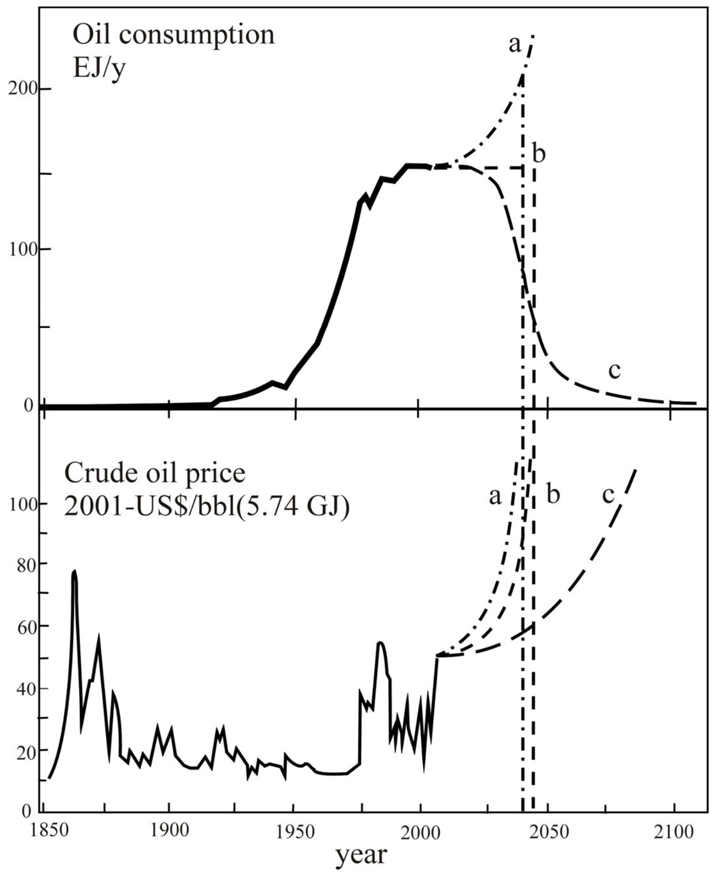

Figure 2. The historical global consumption of oil (top) and the historical price levels of crude oil (bottom), supplemented with 3 models for future behaviour: *a* extrapolates the expected growth in demand, notably carried by countries such as China and India, *b* assumes a constant usage of oil (i.e. all growth substituted) and *c* is a Hubbert model (51) based on the assumption of generously available substitute fuels at prices similar to that of current oil. The rapid price increases in the models *a* and *b* simply reflect the lack of available substitutes for oil at equivalent prices under 100 US$/bbl. The figure is from (1) and uses historical consumption data from a range of sources given in (1) and historical prices from (49) and (50).

The analysis above provides a clear indication of the importance of making viable energy alternatives, including hydrogen technologies, available as soon as possible, and emphasises the urgency of getting R&D started in order to achieve the technical maturity and economic acceptability levels aimed for. At the same time, it is clear that hydrogen technologies cannot reach a penetration in the marketplace large enough to solve the near-term problems. Other solutions are required for the short term, and as underlined by several investigations, efficient use of energy is the only technology that is ready and can be implemented in time (1, 7, 53, 54). The detailed implications of this option will be investigated in section 7.

2. Hydrogen production and storage

The assessments made in recent work, including that of the 4 technical committees of the Danish Energy Agency (58-61), suggests the following areas of particular interest for the introduction of hydrogen. They may bear fruit individually or in combination.

- Hydrogen production based on renewable energy sources.
- Hydrogen used as energy store in variable renewable energy systems.
- Applications of hydrogen and fuel cells in the transportation sector.
- Stationary applications of fuel cells in building environments.
- Stationary application of fuel cells in large power plants.
- Portable applications of fuel cells.

Below, these options are briefly assessed on the basis of the existing information, leading to an outline of technology development trends and costs. This constitutes the basis for a set of proposals for development efforts (in the US called "roadmaps", in Europe "action plans") in the hydrogen and fuel cell area, with emphasis on the areas identified as interesting from a Danish point of view.

2.1 Hydrogen production

Most industrial hydrogen is currently produced from natural gas by steam reforming, with a small fraction produced by alkaline electrolysis, in cases where electricity is the most practical source of energy (1). For use in the energy sector, the natural starting point is energy that cannot conveniently be used directly. In a Danish context, the dominant source of such energy will be wind power, due to the increasing share of wind in the Danish energy system, combined with the intermittence of wind power production. Currently, wind power fluctuations are handled by international electricity trade, but there are limits to the amounts of power that can be handled in this way, because it may occur at times where neighbouring markets have no need for the Danish surplus power and hence draw low prices (e.g. on the Nordic auction pool systems in place, and eventually on a European exchange market).

We have investigated the current frequency of low power market prices in Western Denmark as well as the prospects until 2010 (56, in appendix A). The idea sometimes suggested is that when the price of power is low (such as presumably during windy conditions), the excess may be better used to produce hydrogen than to sell at near-zero revenue. It is found, that near-zero prices presently are too rare to warrant dedicated hydrogen production, and that such occurrences are not systematically correlated to high-wind conditions. The same is true in the near-future (to 2010), and excess wind power is even declining despite increased installed power, because the movement of small combined heat-and-power producers to the market-based system is reducing their share in excess power production at critical times. The market prices for Western Denmark by 2010 averages at 175-275 DKK/MWh depending on prices in neighbouring countries (e.g. caused by dry or wet years for the Norwegian hydro system). The price is within the range of 100-350 DKK/MWh during some 90% of the time. Furthermore, if hydrogen producers appear on the market, this will presumably influence prices in the direction of having fewer hours with low prices. In consequence, hydrogen producers would have to be willing to pay power prices of up to 250 DKK/MWh in order to operate their plants for near 50% of the year. The electrolyser plant capital and operating cost has been estimated as 250 DKK/MWh of electric input (57), leading to a hydrogen price at the point of production of around 0.70 DKK/kWh or 23 DKK/kg. This cost level is similar to estimates from other sources (1, 62, 63, 64).

The cost estimated for hydrogen produced through biomass gasification is only slightly higher (depending on the price of biomass/waste) than that from electrolysis (62), while production by coal gasification is estimated to be higher (64). Electrolysis by fuel cells in reverse operation may attain high efficiency (1, 6), but at the moment, fuel cell costs are prohibitive. The current reference cost for hydrogen produced from steam reforming of natural gas is of the order of 10 DKK/kg at US gas prices (62), but higher at Danish prices[¤]. Hydrogen production based on fermentation of biomass and other biological schemes may become economically attractive alternatives (58).

[¤] One should generally be careful in using cost estimates from countries with a different taxation and subsidy policy from the country studied. This applies in particular to the US costs for end-use technologies quoted in the following.

2.2 Hydrogen storage for renewable energy systems

In order for fluctuating renewable energy sources such as wind and solar radiation to attain a dominating share in any energy system, storage must be part of the system. Only for modest levels of penetration can demand-supply mismatch be handled by trading (e.g. in international power pools). Sudden large imports are costly and sudden spot-market exports must accept low prices. In any case, a trade-based solution to the mismatch problem only works if neighbouring systems are based on systems that can adjust their production arbitrarily (i.e. fuel-based or hydro systems). If the transition to variable primary sources is taking place globally, there is no alternative to energy storage. An assessment of possible energy storage technologies (7) does not identify any other storage option more suitable for the Danish system than hydrogen underground storage. The options of aquifer or salt intrusion storage are natural extensions of their proven usefulness for natural gas storage and promise a very low storage cost. In areas of the world without these options, rock cavern storage is technically feasible but somewhat more expensive.

This indicates that hydrogen as a storage medium to use in connection with variable renewable energy systems based on wind turbines or photovoltaic collectors is an option that likely should be used, independent of the outcome of the development of fuel cell technologies towards a wider role for hydrogen in the energy system. Without fuel cells, conventional methods for regeneration of electricity from hydrogen (e-g. gas turbines, Sterling engines) have to be used, implying a lower efficiency than that of stationary fuel cells, but not in a dramatic way (40-50% rather than 50-65%).

In conclusion, the use of hydrogen stores would be part of any energy policy aimed at replacing environmentally adverse reliance on fossil fuels (with declining supply security due to resource and political constraints) by renewable energy technologies. The urgency of introducing bulk energy storage is larger for Denmark than for most other countries, due to the very high penetration of wind power already achieved.

2.2.1 Estimated hydrogen storage costs

Hydrogen storage costs comprise capital cost for the equipment used and operational costs, such as power for compression or liquefaction. (25) quotes the additional cost of hydrogen recovered from a liquefied store as about 5 US$/kg for small units, decreasing to around 1 US$/kg for high compressor/liquefier rating. The additional H_2 cost going through a compressed hydrogen store in containers is around 0.4 US$/kg for short-term storage, but rising with length of storage (26, 27). The large scale underground hydrogen storage in caverns, abandoned natural gas reservoirs, aquifers or salt discussed in (1) have much lower costs (capital cost of establishing the store at 3-20 US$/kg, leading to a storage cost of one order or magnitude below that of liquefied H_2 storage and two orders of magnitude below that of compressed storage) and constitute a natural choice for centralised storage of hydrogen.

For decentralised stationary storage, metal hydride stores or one of a range of similar concepts (see ref. 1) may be more attractive than compressed gas flasks, but the cost is difficult to estimate at present (lacking knowledge of which hydrides to use as well as the best geometrical design that would allow extraction sufficiently rapid for e.g. automotive applications). Capital costs for metal hydride stores have been estimated as being in the range of 2 000-80 000 2004-US$ per kg H_2 capacity (26). The storage cycle costs are estimated at 0.4-25 US$/kg (27). If successful, such stores may also be considered for automotive applications, although the weight will be a problem except for some non-metal chemical or carbon storage types. Best current guesses are for a cost that is at least twice that of compressed storage containers.

3 Fuel cells and vehicle applications

The transportation sector is clearly the sector where a transition to sustainable energy sources is most difficult as well as most needed. For the past several decades, hopes were placed in battery-based electric vehicles, but it has taken long time to reach the technical goals for battery performance, and the economic goals that would make a purely battery-operated vehicle with suitable range economically acceptable have not yet been reached. As a consequence, automobile manufacturers have lowered the expectations to battery-driven vehicles and instead hope that the fuel cell vehicles under development will one day be able to meet both technical and cost goals. The analysis made in Chapter 4 of (1) indicates that this may not be the best approach, because fuel cell-battery hybrid vehicles may well turn out to be the optimum solution, due to the complementary advantages of the two systems. The current emphasis on PEM fuel cells requires substantial further technological development of PEM fuel cells in regard to reliability and long service life, and particularly in regard to cost, especially if the fuel cell has the total responsibility for powering the vehicle. The hybrid fuel cell-battery option may offer full performance with a lower sum rating of the two systems, as compared with both pure fuel cell vehicles or the pure battery-operated vehicles (see Appendix B.1)

If the PEM fuel cell development does not meet the set goals, a possible alternative would be acid polymer cells operating at temperatures around 200°C. However, the development stage of this concept is currently much less advanced, and a shift to this technology will likely have the effect of further delaying the deployment of viable vehicle fuel cells in the general automobile manufacturing lines.

Assuming that the PEM fuel cells do reach the technical goals, their introduction will depend on the cost reduction development linked to market penetration issues and hence accumulated mass production. This phase can be speeded up by creating infrastructure facilities at an early stage, and by market introduction initiatives involving a reward for the absence of pollution during operation of the fuel cell vehicles (and also during hydrogen production if this is based on renewable energy sources). The transition is influenced by the possible availability of fuel cell-battery hybrids, because this gives each improvement in either technology a positive impact on cost. A catalytic role may be seen for the currently available gasoline-battery hybrids, which can help lowering the cost of advanced batteries and make their deployment if fuel-cell-battery hybrids happen at an earlier stage.

Initial introduction of fuel cell vehicles may be in applications where the range requirements are modest, such as fixed-route buses, delivery vehicles and off-road vehicles. Also the markets for fuel cell trains and ships seem more interesting than current activities indicate. The auxiliary system components should not be neglected, as cost of filling stations and particularly transport/transmission systems for delivering hydrogen to these (or producing it on-site) can substantially influence the overall attractiveness of a fuel cell system.

3.1 Cost of PEM fuel cells for automotive and stationary applications

The PEM fuel cell technology has reached a stage of both prototypes, zero'th order serial production (the Ballard Mark 902) and several application demonstration programmes. It is thus of interest to discuss the learning curve behaviour of the future cost of this technology.

More recent estimates of the gain by mass introduction of PEM cells into vehicles arrive at a future cost as function of both the accumulated volume of production and two additional parameters: power density improvement (increasing from current 2 to 5 kW/m^2) and speed of maturing (taken as slope of an assumed logarithmic learning curve) that ranges from 15 to 392 US$/kW (11). The lower cost estimate assumes an optimistic accumulated 5 million fuel cell vehicles by 2020, with average rated fuel cell power of 110 kW, while the upper estimate assumes 50 000 vehicles and a fuel cell power density having reached 3 kW/m^2, the cost being suggested to be a possible minimum achievement for the year 2010.

Vehicle PEM fuel cells are currently designed for a life time of around 5000 h, in contrast to the 40 000 h set as the minimum for continuous stationary uses. Presently, the semi-commercial PEM cells used e.g. in small series of fuel cell vehicles do not even reach the 5000 h lifetime goal. For PEM fuel cells used in stationary systems, ref. (12) estimates a break-even price of 1200 US$/kW for 5 kW home systems and 700 US$/kW for larger, 250 kW systems (for given expectations of future US fossil fuel prices; with European prices and taxes the break-even price will be about twice as high). Vehicles when parked in a garage could contribute to electricity production for the building system. This would require fuel cell lifetimes as for stationary uses.

The current introduction of the first small-series semi-commercial fuel cell units, for vehicles and for building usage, should provide a better basis for predicting cost reduction potentials in the long term. It may be instructive to compare with the empirical learning curves for other technologies in the energy sector, such as wind and photovoltaic power, or with high-density battery developments. Figure 3 gives the results of an analysis of the wind and photovoltaic learning curves. Economists often describe such findings in terms of a straight line logarithmic behaviour, writing the cost Y as function of accumulated volume of production X, $\log Y(X) = -r \log X + \text{constant}$. The slope $-r$ is sometimes quoted in terms of a "progress ratio" $PR = 2^{-r}$ or the "learning rate" $LR = 1 - PR$.

Figure 3 shows that quite complicated features are found in empirical learning curves (given in 2004-euros by use of deflators from (19)).

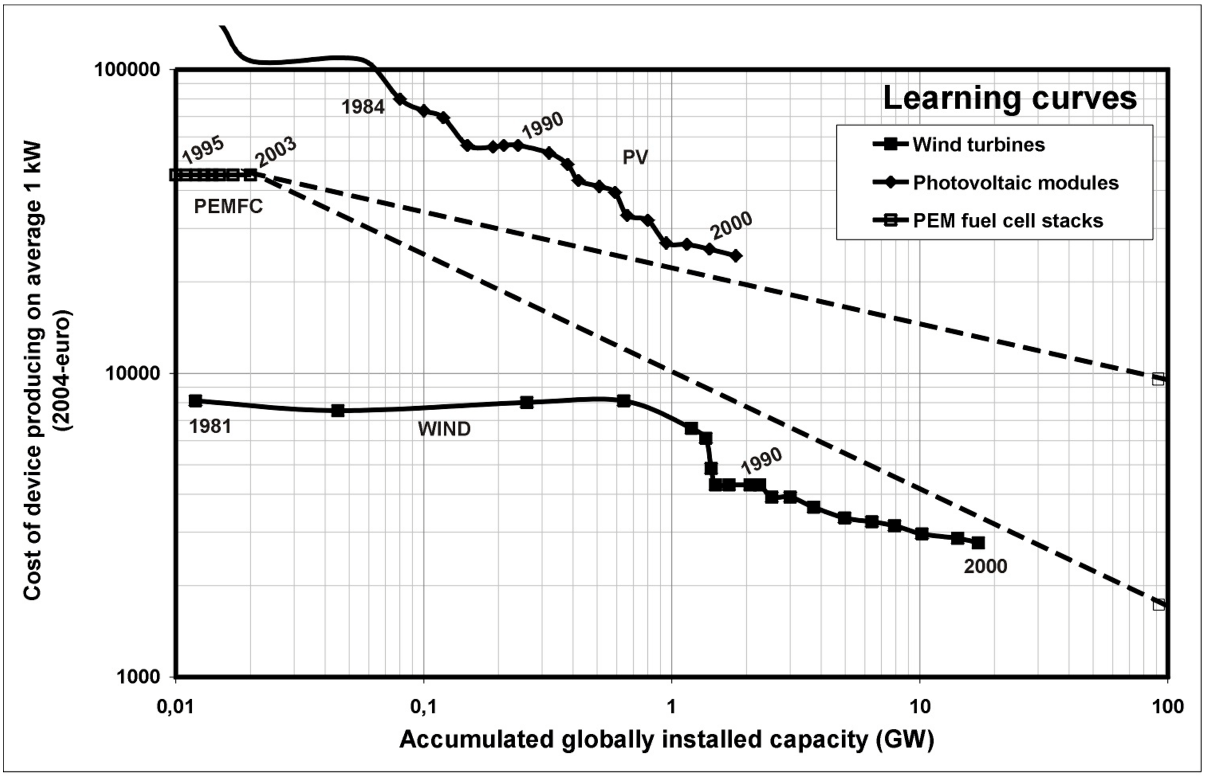

Figure 3. Observed learning curves for wind turbine and photovoltaic module costs used to suggest possible learning behaviour for PEM fuel cell stacks. The total accumulated capacity at a given time is along the abscissa, the average cost of power production is along the ordinate. The latter is taken as the cost per kW of installed power divided by c_P, which is the ratio, assumed constant, between average actual production and the device rated power level (or alternatively stated the equivalent fraction of time with power production at the device rated maximum power). The two dashed extrapolation lines for automotive PEM fuel cells correspond to learning at the rates characterising the wind and photovoltaic industry, respectively, during recent years. Data for wind turbines are based upon (13) and (14), using globally installed capacities from (15) and turbine list prices from Danish manufacturers (16). The average production estimates assume a class 1 location, which represents the best on-shore sites in Denmark, but is inferior to Danish off-shore sites and to on-shore sites in windy locations such as the west coast of Ireland. Data for photovoltaic modules are from (17) and (18) , based on European Photovoltaic Industry Association and Strategies Unlimited 2003 costs and shipping data. The early penetration PEM fuel cell cost is based on Danish Hydrogen Programme tenders 1998-2001 and on European Commission *Citaro F* bus project estimates 2002 (1).

Looking at the wind turbine costs, the flat or rising cost curve during the 1980ies reflect a period, where tax evasion schemes made it possible to sell wind parks in the USA (particularly California) without worrying too much about cost. By the end of the decade, the Californian market collapsed and prices rapidly went down in an effort to penetrate new markets in other parts of the world. This was not successful and several manufacturers went bankrupt (vertical part of the curve). After a restructuring of the industry, the diversification strategy worked better, and after a few years with a flat cost curve, the markets really took off and learning curve behaviour set in. The recent decade exhibits a learning rate of about 10% in a steadily expanding market (Germany, India, Spain, Denmark plus several others). The curve in Figure 3 pertains to the performance at a class 1 wind condition site, where the coefficient of performance has raised to $c_P = 0.294$ by year 2000, compared with 0.20 by 1981. The last four years, expansion has particularly been in offshore wind farms, where the coefficient of performance is as high as 0.46 (7). This is not due to any radical technical modification, but rather to a change in design philosophy away from aiming at maximum annual energy production to one, where more annual operational hours has a higher priority (in practice obtained by keeping the blade design and pitch angle roughly as it were for the on-shore turbines).

For photovoltaic panels, the straight-line approximation works better, but closer inspection of the curve reveals a jumping from one plateau to a lower one each 3–5 years. This reflects the improvement in technology, each time new production equipment is introduced, but a competing influence is from the many public subsidy programs (particularly in Germany and Japan). These make it less attractive for the manufacturers to decrease prices, but they are eventually forced to do so by the tender condition set by the large public programmes. The overall learning rate is slightly above 20%, e.g. considerably higher than for the more mature wind technology. The coefficient of performance is around 0.16, meaning that on average over a year, the panels produce energy corresponding to 16% of the one they would have produced if operated in full solar radiation at their maximum (rated) power all seasons and day and night.

Turning now to PEM fuel cells, the emerging technology nature does not allow even a starting price to be determined with much accuracy. In 1995, fuel cells were sold to research laboratories and prototype vehicles at prices lower than the starting price shown in Figure 3. However, these cells were without any warranty and often worked for less than a year. When the technology started to take off around year 2000, with PEM fuel cell buses and passenger cars coming into operation by 2003-4 in small series of 30-80 units, most fuel cell manufacturers entered contractual agreements with automobile manufacturers, at prices not generally known. Efforts to purchase PEM fuel cells by national programmes faced difficulties, and the few manufacturers willing to quote prices demanded much more than in 1995. The market is still for test series, and the cells do not yet have the goal 5 years of operational life. The prices used for Figure 3 are taken from such tenders and from the European bus project material, assuming that the cell price constitutes about half of the total system price (the estimated cost of a *Citaro F* bus relative to a similar bus with a conventional diesel traction system). The power coefficient c_p is taken as 0.12, corresponding to 5000 hours in operation over 5 years. This is probably a high estimate, as the vehicles would not be operating all their driving time at full fuel cell rated power (except possibly for hybrid cars charging batteries with excess power).

The future reduction in PEM fuel cell prices is indicated in Figure 3 by two curves corresponding to learning rates of 10 and 20% corresponding to the limiting cases of photovoltaic modules and wind turbines over the recent decade. Even with the lower curve, break-even with current vehicles would not be reached until the cumulated production has reached about 500 GW. However, difficulties mentioned in section 1 for the market for oil products (peaking production, instability of major supplier countries) may make PEM fuel cell vehicles competitive earlier and at higher prices than the currently seen break-even price.

This discussion has shown that many factors influence price development, in addition to industrial "learning". One should also be careful with methods used in the literature, which are often very different one from another, e.g. using running instead of as here inflation-corrected prices, or comparing prices and cumulative installations only for a single country (20, 21). The learning of manufacturers in a single country is unlikely to be a reasonable indicator, because technological progress spreads rapidly across regions. Prices, on the other hand, may vary geographically due to a new kind of industry not possessing the sales and maintenance infrastructure world-wide, which is why costs for a particular country has been used in Figure 3. Another reminder is that use of double-logarithmic plots can make just about anything look linear, especially if several decades are included for both abscissa and ordinate. Care has been taken in Figure 3 not to encourage this feature, which is striking in a large part of the literature on the subject of learning curves.

A final warning regards comparing prices of energy-producing equipment with different lifetime. Wind turbines have an established lifetime of around 25 years. The lifetime of photovoltaic panels are believed to be similar or even longer, at least for those based upon crystalline and multicrystalline cells. In contrast, the 5-year lifetime currently aimed at for both automotive and stationary fuel cells should be considered in comparing technologies. One may thus argue, that the fuel cell curves in Figure 3 should be moved upwards by a factor of five, if the purpose is to compare different technologies. The break-even point of fuel cell vehicles is not affected, because it is already based on the assumed equipment life. Only in case the lifetime goal cannot be reached (or is surpassed) will the assessment have to be modified.

The time required to meet the target costs for both stationary and mobile PEM fuel cell systems have been explored by the Delphi method (interviewing a number of experts) (22). The result was a distribution centred around 17 y for both technologies. It matches very well the assumptions of e.g. Tsuchiya (23) mentioned above and is consistent with the goals of 40-200 US$/$kW_{rated}$ expressed as needed to break-even in regional fuel cell programs in Europe, Japan and the USA (2-4, 24). The fact that the United States estimate of the break-even price is at the lower end of the range is due to the low price (ignoring externalities) of current subsidised vehicle fuels in that country.

3.2 Estimates of infrastructure costs

The cost of hydrogen transmission by pipeline depends on the pipe diameter and hydrogen flow rate. By increasing the pressure difference through the pipeline, cost can be reduced more than the additional cost of compressors. (26) arrives at a cost of about US$ 5/GJ for an optimised flow rate of 10^6 kg per day through a 160-km pipeline. The cost of liquid hydrogen transport by road is estimated as lower, but using current levels of transportation fuel (diesel) costs, and in any case the additional cost of liquefying the hydrogen (plus efficiency losses and boil-off problems) makes the total price unattractive except for the very longest transportation distances (such as intercontinental hydrogen transport by ship).

Converting filling stations for road vehicles to dispensing compressed hydrogen may add some 0.1 US$/kg to the hydrogen price, but alternatively, the hydrogen production may take place at the filling station site using any of the methods available. The cost of converting a reasonable number of filling stations is less than one year's maintenance costs for the current system (cf. review in (27) and (28)).

In-building generation of hydrogen (be electrolysis, likely using fuel cells) and dispensing to garage-parked vehicles ("one-car filling station") are likely to double the price of hydrogen production and filling, respectively (27). Decentralising hydrogen production changes the infrastructure problem to involve a possible reinforcement of the electricity grid rather than establishing a hydrogen grid, which in economic terms would seem an advantage (1, 29).

In case hydrogen is produced from natural gas during an interim period, it may be considered to recover CO_2 (which is already separated in most current steam reforming plants) and store it away from the atmosphere, e.g. in abandoned wells or as carbonate on ocean floors. This procedure is by many considered as unproven and potentially environmentally dangerous (see discussion in ref. 1). The additional cost is estimated at 0.05-0.1 US$ per kg of hydrogen (27).

3.3 System costs

The cost of fuel cell systems is partly the cost of vehicles (or of building-based systems for stationary applications), and in a wider context the total cost of a hydrogen economy with production, various types of usage and infrastructure such as storage and transmission, distribution and filling outlets.

One reason that system costs may reveal things not possible to derive from the component costs is that each system component has an efficiency characteristics that often differs from that of the equivalent component (if there is one) in the current energy system.

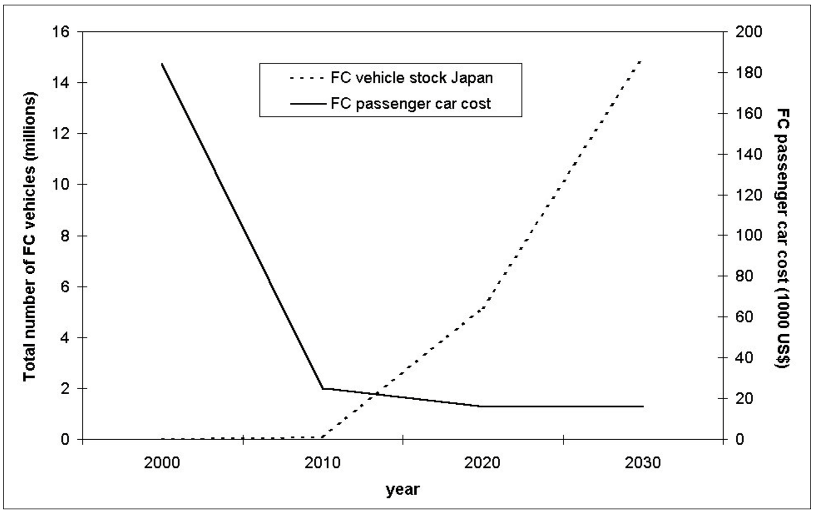

Figure 4. Scenario results for market introduction of fuel cell vehicles in Japan, giving the stock of FC vehicles as function of time, along with the decline in cost of passenger FC cars (the stock comprises other types of vehicles as well) (1, 23).

Looking specifically at the cost of PEM fuel cell vehicles, the studies aimed at probing into future fuel cell costs have also addressed the total system cost of fuel cell, hydrogen storage, handling, batteries in case of hybrid vehicles, and power control, in order to arrive at a total price development of car manufacture. Figure 4 shows the result of a Japanese study, with assumption of a fuel cell cost declining to 40 US$/kW by 2020 (one of several scenarios) and a corresponding increase in the stock of fuel cell vehicles (passenger cars, lorries, buses etc.) to 5 million by 2020 and 15 million by 2030. One might have expected the demand for fuel cell vehicles to rise as the price comes down and not only after it has come down, but the scenario is just an indication for three selected years and does not pretend to be dynamic. By 2020, the fuel cell vehicle cost (15 788 US$ in constant $'s) is nearly as low as that of current gasoline cars (13 136 US$ assumed in the study).

Figure 5 shows the amounts of hydrogen required in the Japanese scenario, along with the associated cost. Figure 6 shows the number of hydrogen filling stations required and the annual cost of constructing them.

The scenario assumptions made by (11) comprise a slightly declining population in Japan, a modestly rising gross national product, an unchanged demand for energy (achieved by the introduction of more efficient energy using equipment, not only in the transportation sector). The production of fuel cell vehicles rises from 50 000 in 2010 to 1.3 million in 2020 and 3.1million per year in 2030, by which year the annual sales revenue is 59 × 10^9 US$ (production cost plus a 15% mark-up). The hydrogen activities constitute 1% of total Japanese GNP by the year 2030.

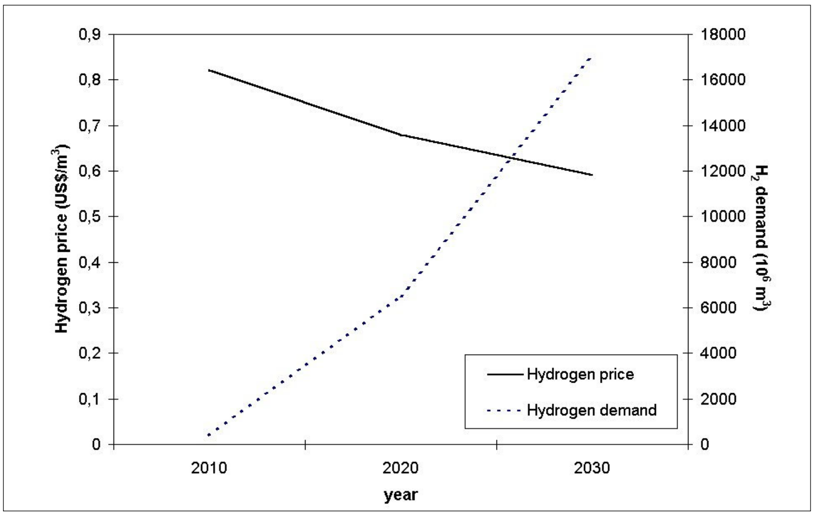

Figure 5. Japanese hydrogen demand and price delivered to the customer in the scenario of Fig. 2 (1, 23).

The cost estimates of key hydrogen handling equipment could be used to expand cost scenarios such as the Japanese one for road transportation to other sectors, e.g. the building integrated use of fuel cells envisaged in the decentralised Danish scenario described in (1, 29). In any case, such cost projections a highly uncertain, due to the wide range of future costs that may materialise for some of the most important components in a hydrogen based energy system (cf. Figure 3).

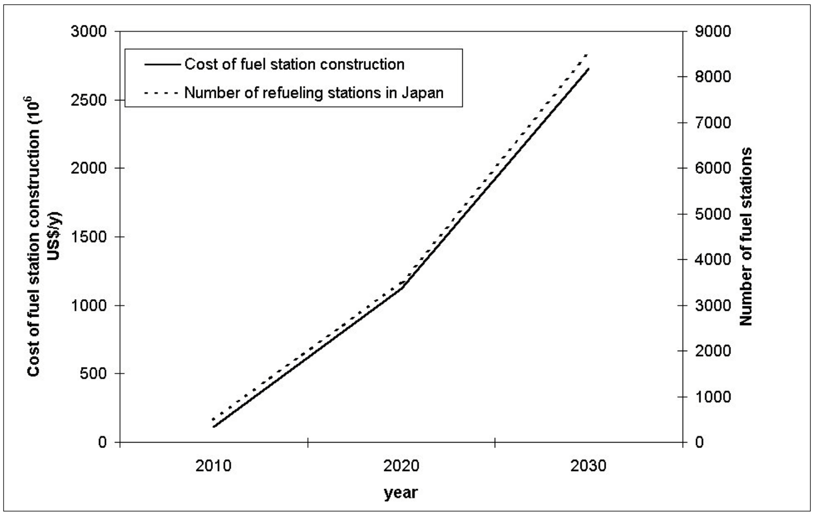

Figure 6. Japanese requirement for hydrogen filling stations and their cost (annual expenditure) for the scenario of Fig. 2 (1, 23).

3.4 Life-cycle analysis of hydrogen PEMFC car and current alternatives

National policy has to be based upon the costs seen by society, which means that social costs (externalities) should be added to the market costs (7, 30). A few life-cycle assessments have been published for fuel cell prototypes and several more for passenger cars with PEM fuel cells. Below, the results of a currently state-of-the-art study are presented.

The passenger cars selected for this LCA analysis are characterised by the features listed in Table 1. The DaimlerChrysler f-cell is the first fuel cell passenger car to enter the stage of limited series production (estimated at 60-80 units) for demonstration in Japan (31) and subsequently in Europe and the USA. It follows the *Citaro F* fuel cell bus entering a similar phase in 2003 (demonstration in Europe of a small series of about 30 units). The f-cell car is based on a slightly longer version of the commercial A2 series of Mercedes-Benz gasoline and diesel fuel cars, and Table 1 reflects the data available early 2004. The two non-fuel-cell cars studied for comparison are a Toyota *Camry* gasoline/Otto engine car used as a typical US year-2000 vehicle in a previous life-cycle study (32, 33), and the *Lupo 3L TDI* Diesel car topping the European list for mixed driving efficiency (34, 35). Table 1 gives a gross material usage survey, as well as the weight and fuel consumption details to be used in the life-cycle analysis. These are summarised in Figures 7 and 8.

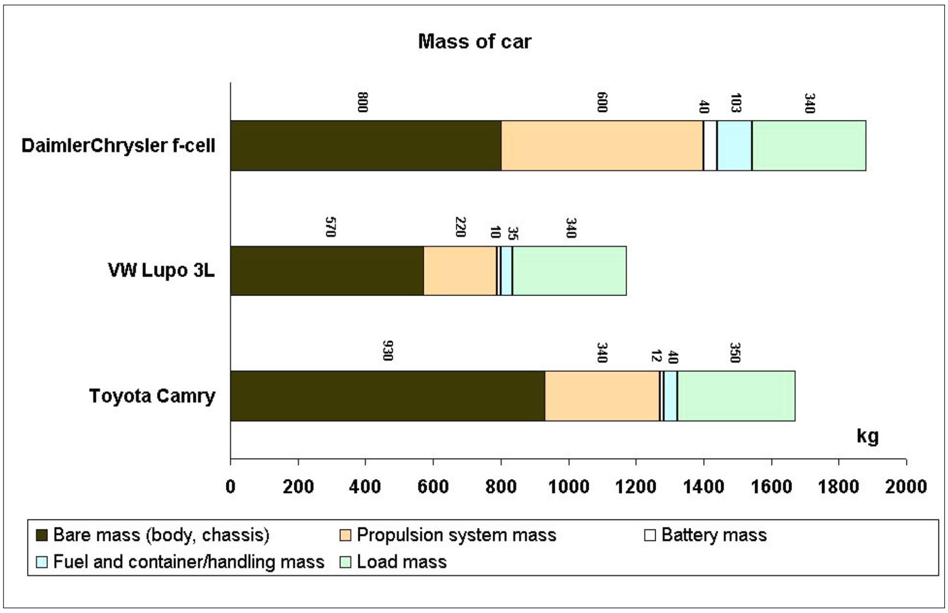

Figure 7. Comparison of mass distribution for the three passenger cars included in the LCA analysis (1).

Passenger car (1-5 persons plus luggage) **Description**	average USA, 2000 Otto engine Toyota Camry	best Europe, 2000 common-rail Diesel VW Lupo 3L	35 MPa H_2 fuel PEMFC/elec. motor DaimlerChrysler f-cell	*unit*	*reference*
Bare mass (body, chassis)	930	570	800	kg	3,4,7,est.
Propulsion system mass	340	220	600	kg	3,est.
Battery mass	12	10	40	kg	3,4, est.
Fuel and container/handling mass	<40	<35	3+100	kg	3,4, est.
Proper mass (unloaded)	1300	825	1589	kg	4,5,6
Mass of steel		410		kg	4
Mass of plastics, rubber		130		kg	4
Mass of light metals		130		kg	4
Load mass	<350	<340	<340	kg	3,4
Total mass (occupancy: 2, 0.67 full tank)	1440	980	1725	kg	3,4
Coefficient of rolling resistance	0.009	0.0068	0.0068		3,est.
Drag coefficient	0.33	0.25	0.25		3,4
Auxiliary power	0.7	0.6	1	kW	3,est.
Engine/fuel cell rating	109	45	69	kW	3,5,6
Electric motor rating			65	kW	5,6
Battery rating		4/732	20/71400 (§)	kW/Wh	5,6
Reformer efficiency (not applicable)					
Engine/fuel cell efficiency*	0.38	0.52	0.68		3,7,calc.
Gear and transmission efficiency*	0.75	0.87	0.93		3,est.
Electric motor efficiency			0.8		3
Fuel use*	2.73	1.08	0.8-1.44¤	MJ/km	3,7,calc.
Fuel use*	12	33		km/l	3,4,5
Fuel to wheel efficiency*	0.15	0.27	0.36		3,calc.

Table 1. Basic vehicle data used in LCA study (1, 36). Caption continued next page.

* For standard mixed driving cycle. Fuel to wheel efficiency is the work performed by the car to overcome air and road friction, plus the net work performed against gravity and for acceleration/deceleration, all divided by the fuel input (note that this efficiency concept varies linearly with the combined drag and rolling resistance).
§ Nickel metal hydride battery
¤ 0.8 assumed in LCA, 1.44 MJ/km quoted by DaimlerChrysler (Japan) for first batch.
Key to references: 3: (32); 4: (34); 5: (35); 6: (31); 7: (33).

Figure 7 shows that while the *Lupo* has diminished weight as compared to an average car through use of lightweight materials where possible (but still being in the top safety category according to crash tests), the f-cell car, although small of appearance, has a higher mass than even the conventional car, due to the heavy equipment associated with hydrogen management and conversion. Figure 8 compares the efficiencies of the three cars studied. In terms of energy content, the hydrogen for the f-call car is slightly below the Lupo, both being considerably below the current average car. The fuel-to-wheel efficiency improves considerable for the fuel cell vehicle, over the efficient diesel car and of course over the conventional gasoline car. Fuel use is obtained by simulation, using the new European driving cycle used for official rating of cars in Europe. Details of environmental and social LCA cost analysis may be found in ref. (1, 36) or Appendix B.2.

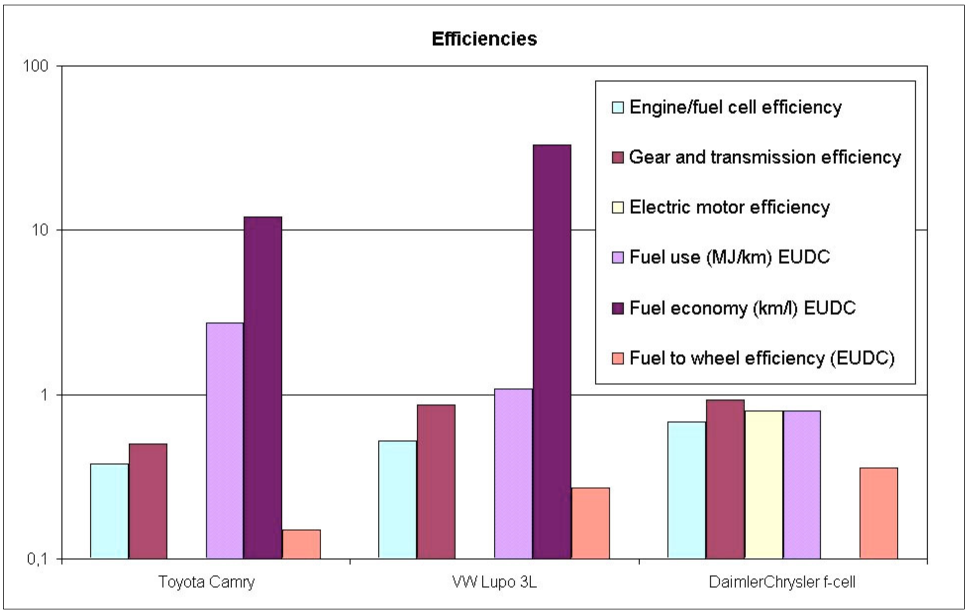

Figure 8. Comparison of contributions to and total efficiency of the three cars studied in the LCA analysis (1). As indicated in the insert, two columns carry dimensions, while the rest are dimensionless efficiencies. The first f-cell cars demonstrated in Japan and Australia during mid-2004 has an 80% higher fuel use than indicated here.

The cost of the f-cell car is not available at the present time, but has been taken as that of the corresponding Mercedes-Benz (smallest model) plus a fuel cell stack taken as 100 euro/kW, and the other hydrogen handling and storage costs are assumed to be similar to that of the stack. Finally, a factor of two is applied due to the small series of production. This price distribution is similar to the one estimated for the *Citaro F* fuel cell bus. Maintenance costs are taken as a fixed fraction of capital cost and thus large for the f-cell car (hardly unrealistic for a new construction). The hydrogen cost is that of production from natural gas, ramped down as a function of time. It does not include the initial high cost of establishing hydrogen filling stations. No separate estimate is made for the cost of producing hydrogen from wind, discussed in (29). The fuel price for gasoline and diesel fuel has been taken at the current level, disregarding possible increases during the period of operating the vehicles.

One may attempt to translate the externality costs (i.e. those not reflected in direct consumer costs) into monetary values. This involves translating the impacts from physical units to common monetary units, with the problems inherent in such an approach, notably valuing the loss of a human life to society. The caveats are associated with the fact, that impacts such as accidental deaths are not always occurring in the same society that harvests the benefits of car driving. These issues have been discussed, e.g. in (7).

All monetised impacts are summarised in Figure 9, for the three vehicles considered. A very large fraction of the impacts derive from road infrastructure, traffic accidents and annoyance. These are identical for all vehicles, except for noise that is smaller for hydrogen vehicles. The other large contribution is from emissions of pollutants to the air. They are in part from manufacture and maintenance, and in case of the gasoline and diesel cars from emissions in breathing height, despite attempts of exhaust cleaning (much less efficient than for central power plants). This component is larger for the average car than for the Lupo 3L, as is the fuel cost. Regarding greenhouse gas emissions, the f-cell car using hydrogen from natural gas is no better than the Lupo car, but with hydrogen from renewable energy sources the advantage is substantial.

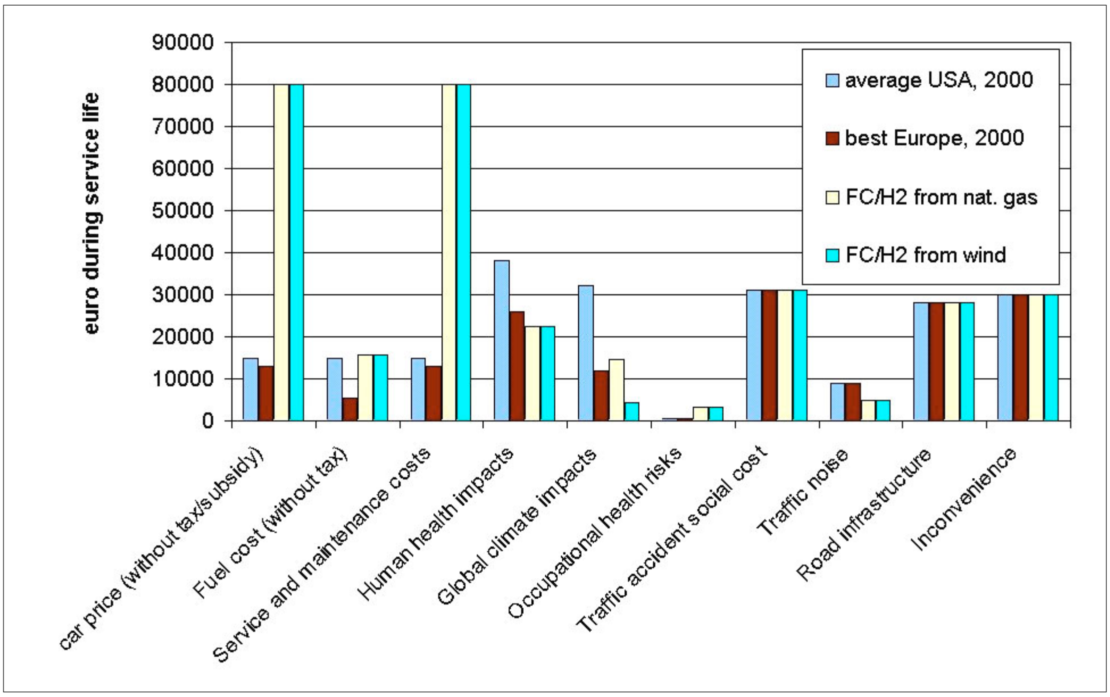

Figure 9. Summary of monetised life-cycle impacts (1, 36).

Concern over particulate air emissions involving small-diameter particles have made some countries prefer gasoline cars over diesel cars, except for trucks and buses where the higher efficiency has been the overriding factor. The mechanisms involved in the dispersion of such particles has been the subject of intense study (see e.g. Kryukov *et al.*, 2004). The Lupo diesel car considered above has reduced the particulate emissions (see Appendix B.2) to levels comparable to those of gasoline cars, but newer European diesel cars, including both efficient passenger cars, buses and trucks, have electrostatic filters reducing the particle emissions by over 90%, which is better than the SO_2 removal by the small catalyst devices used in gasoline cars (but in both cases not as good as the exhaust cleaning at large, stationary power plants).

For fuel cell cars carrying methanol and using an on-board reformer, there is direct emission of greenhouse gases, as well as additional impacts from manufacture of fuel and reformer, leading to an overall CO_2-equivalent contribution some 10% higher than for a corresponding car with pure hydrogen fuel stream (38, 41-43).

4 Building-integrated fuel cells

The PEM fuel cell with heat extraction is the choice by many manufacturers for building-integrated applications, where multi-functionality would allow current natural gas burners to be replaced by combined power-and-heat (CPH) systems, possibly with the additional option of supplying hydrogen to a one-vehicle filling station. One may think that if the automobile industry is successful in developing a viable PEM fuel cell for vehicles, then it will be directly applicable for stationary purposes. However, this is only partially true, as the service-life requirements are much higher for stationary uses. The aim at the current natural gas customers implies that a gas reformer needs to be integrated in the system. The customers that currently have access to piped natural gas is only a segment of the total market, with a share that varies between countries. Also SOFC CPH installations at the 1kW-level (efficiency 23%) are being tested in a few places (65, 67).

Looking a bit further ahead, an interesting system is that of a reversible PEM cell capable of converting excess electricity supplies (from renewables) to hydrogen for moderate time storage. A break-through in the efficiency of the PEM electrolysis operation of specially designed PEM cells (1, 6) makes this an interesting solution (with parallels in the filling station on-site conversion), and the remaining problem is suitable hydrogen stores for safe operation in building environments (beyond what can be directly stored in vehicles parked at the building, cf. Chapter 5 in (1)).

Overall, the cost and technical performance of PEM fuel cells exhibit the same problems for decentralised stationary as for mobile applications, with the mentioned qualification that durability requirements are substantially higher. Both applications are in areas, where consumers in most parts of the world are accustomed to paying a fairly high energy price, as compared with that characterising central power plant operators. Only the balance-of-system components are different, especially for early natural gas-based units. Other types of fuel cell systems applications are under development, also in Denmark, such as auxiliary power units aimed at emergency power supply (requiring high reliability and functionality despite infrequent calls, but on the other hand a small number of operating hours). These are sometimes called UPS (uninterruptible power supply) systems.

5 Fuel cells in portable equipment

The current generation of portable consumer products are in several areas close to the technical limits of battery technology. This is true for portable computers, where high performance requirements have led to considerable efforts to make energy use as efficient as possible. Flat screens of very low power consumption has been developed, and both central processors and peripheral equipment is rapidly approaching a very good energy performance. Driving forces in this direction include also the stationary computers, because damage caused by excess heat is a decisive determinant of life time and performance. For these reasons, the current autonomous operating time of some 4 hours between battery recharging is a major limitation both for present users and for further performance development.

This suggests that portable applications may offer a very attractive upstart niche market for fuel cells and small-scale fuel stores, just as they did some years ago for advanced battery types (first NiMH then Li ion batteries). The discussion in Chapter 4 of (1) suggests that the most appropriate technology for this type of application may be a direct methanol fuel cell, due to the volume requirements of the fuel store. Increasing the operational time between reloading to some 10-20 hours, this option offers advantages to users that they would likely be willing to pay a considerable price for, as they already do for advanced Li ion batteries consuming more than 200 US$ of the cost of a portable computer.

Also for the fuel cell development in general, the existence of such niche markets can have a positive effect, reminding of the success of Japanese manufacturers obtained by incorporating solar cells in consumer products such as watches and calculators and thereby earning a profit capable of covering the total Japanese development costs of solar cells, at least for an initial ten year period. Not surprisingly, the development of portable fuel cell equipment takes place almost exclusively in Japan (with a few activities in Germany, Korea and the USA).

6 Fuel cells in centralised power production

Because the current bulk power production sector in Denmark is dominated by coal-fired power plants, the concern over future fuel prices issue is not as strong as for oil in the transportation sector. However, considerations of greenhouse gas emissions put coal low on the list of acceptable fuels, and ways of de-carbonising coal are intensely discussed. Here, primary hydrogen conversion is high on the agenda, because the alternative of recovering carbon from exhaust gases is a fairly low-efficiency and energetically unfavourable options. In case the renewable energy transition is successful in the power industry, hydrogen will as mentioned in Chapter 7 of (1) also have an important role already for central energy storage, even if the regeneration of electricity is not done by fuel cells.

If the higher efficiency of fuel cells warrants their higher cost, the most likely fuel cell type for the bulk power sector is the SOFC. However, there are still many technical issues to resolve, especially if fuels other than pure hydrogen are to be used (the poisoning problem from sulphur or nitrogen compounds as well as chlorides and other halogens mentioned in Chapter 3 of (1)). Because the power sector is not pushing this development as strongly as the automobile sector is pushing the PEMFC development, it may take longer before a cost-effective SOFC is available, or the PEM cells make take over the utility market due to the lower cost achieved through its use in the transportation sector, despite slightly lower conversion efficiency. A special application is for peak-load assistance, where units with modest lifetime expectancy can be accepted. Such units are likely not based on high-temperature fuel cells, because it would be expensive to have them stand-by at a high temperature. Possibilities are PEM cells and MCFC (molten carbonate fuel cells), which are being tested in several countries (68).

The feeling of a lower urgency for introduction of fuel cells in the power sector may not be warranted, considering the possibility of an increased effort to combat the global warming problem by introduction of renewable energy, which has its primary market aim precisely in the area of power generation. The scenarios in Chapter 5 of (1) indicate centralised solutions that may be considerably lower in cost than the building-integrated solutions, due to a possible lower cost of large fuel cell installations (e.g. due to balance of system costs, as the stacks themselves are modular and hence with little scale effect), including stores and taking advantage of often lower cost infrastructure for bringing hydrogen from stores to power plant sites and the availability of existing electricity transport networks, all in comparison with the duplication of many infrastructure components in a multitude of buildings.

7. Scenarios of Danish implementation

Much previous energy planning in Denmark has been based on the scenario method (7, 66). The most recent scenarios for possible utilisation of hydrogen as an energy carrier are 4 scenarios for the years 2030 and 2050 (29). They will need to be updated in the light of new developments. For example, one may consider two hydrogen scenarios: One assumes that current fuel cell development reaches the stage of marketing commercially viable products. The other considers a more restricted use of hydrogen without fuel cells, to allow for the use of large quantities of fluctuating energy sources such as wind energy. Preliminary sketches of the end-point of the two scenarios are given below, with illustration of possible implementation path. Such scenarios may help energy planners see the long-term implication of political decisions made today.

7.1 Energy demand assumptions

Recent trends in Danish energy demand (46) indicate increased energy efficiency in most sectors, leading to a total energy use that has changed little over recent decades despite substantial economic growth. This gives credence to the assumption made in the recent scenario work (29), that by 2050 the average efficiency of energy using devices will equal that of the equipment with best efficiency found on the market in year 2000. Looking at the individual forms of energy use, current trends may be summarised as follows:

The use of low-temperature heat in buildings will remain fairly constant. Earlier growth in per capita floor area in dwellings has stopped, and there seems to be little desire for the average family to have more space to clean and maintain. Also for hot water use for household and bathing it is difficult to see reasons for more growth. The scenarios shall therefore consider low-temperature heat requirements at the end-user as constant over the next decades.

The number of energy-intensive industries has been declining in recent years, and the economic activity is mainly based on a large number of smaller industries, the composition of which is in constant change. The content of industrial activity has increasing fractions of intelligence, a good way to compete with newly industrialised competitor countries. One implication of this gradual change in the Danish industrial activities is that energy use no longer grows. Indeed, it declines a bit due to the disappearing energy-intensive manufacturing. The scenarios assume a 30% decline in end-use energy in industry over the next 50 years. Industry is here taken to include agriculture, silviculture, fisheries and construction. The reduction of areas cultivated that is taking place these years support the assumption of a modest decline in energy use.

The volume of retail trade seems to have developed to a steady size compatible with consumer interests. The service sector is somewhat reclining, because many newer products are technically complex and yet relatively inexpensive, implying that the labour intensive repair of defective equipment is judged as uneconomical relative to purchasing new items. Still, many service jobs still have to be carried out. The scenarios assume that the trade and service sectors reduce their end-use energy demand by 30% by year 2050.

The "soft" commercial sector based on work out of offices (consultants, media providers, etc.) has been growing in recent years. Its energy use is dominated by electronic equipment, as is the end-use energy demand of households, where new devices continue to come into homes and other places of activity (currently devices such as computers and portable phones, but it would not be meaningful to try to guess what new devices may be introduced over a 50-year period). The growth areas are in the scenarios assumed to increase their end-use energy over the next 50 years by 50 and 100% for office and leisure activities, respectively.

Finally, the transport sector is one that has undergone strong increase in energy use over the last decades. It seems to have quieted down, and for road traffic this trend is likely to persist, because few people want to spent more time in congested motorways and streets than today. However, the halt in growth of air travel seen in the aftermath of terrorist attacks during recent years may not persist, and it is rather likely that leisure and business travel will resume its growth, even if some destinations become undesirable as a result of political unrest. In consequence, the scenarios assume that energy end-use demand for surface transportation will grow more slowly, but as it is difficult to substitute, a growth of 30% to year 2050 is still assumed, but including growth in freight transportation. For air transportation, the growth is taken as 50% by 2050. The question of distributing transportation of goods on various modes (lorry, train, ship, plane) is to a large extent a question of government policy through road and rail-line building, tariff structure and so on. The scenarios do not consider further growth, because the strong growth seen in recent decades has to a large extent been caused by the failure of international regulation to compensate the externalities of long-range transportation. This has made differences in salaries to those producing the goods the key economic parameter, while transport around the globe has had negligible impact of the consumer price of imported goods. The question of the future of such diseconomies is difficult to predict, and the scenario choice of not considering further growth in international trade is clearly only one among many possible assumptions.

The concept of end-use is defined in terms of the energy service provided to the end-user, as distinct from the energy delivered to the end-user. Scenario trends in these quantities are depicted in Figures 10 and 11. Figure 10 shows a very modest increase in overall end-use demand, consistent with the trends discussed.

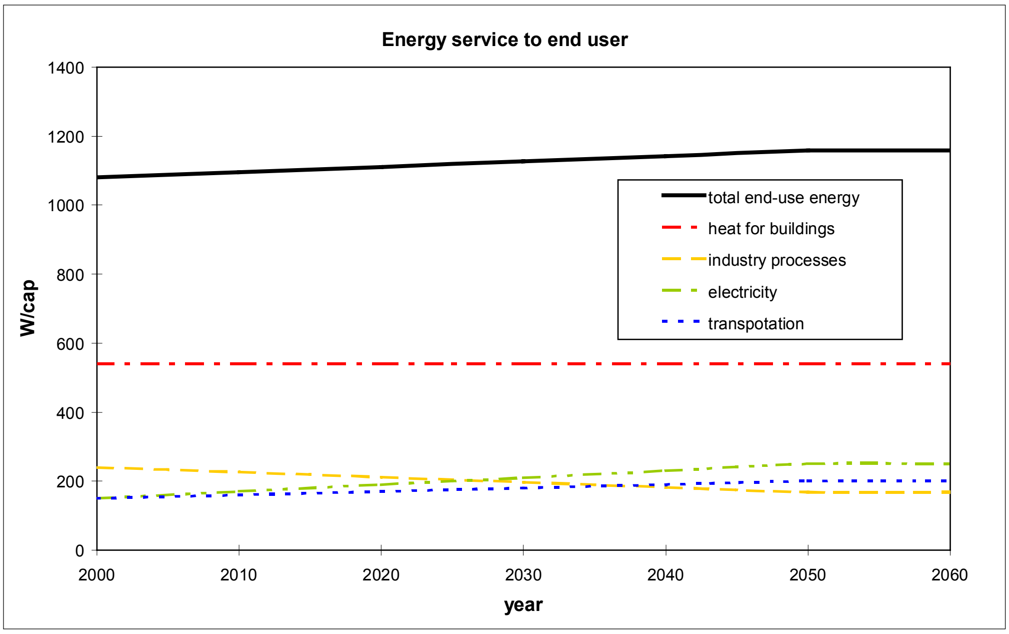

Figure 10. Scenario assumptions on the development of end-use energy demand.

Turning now to the energy delivered to the end-user, it will exceed the end-use energy by the losses incurred in the final conversion from delivered energy to energy service. As mentioned the assumptions from (29) have been used, and Figure 11 shows that reaching an average efficiency equal to the best found on the market today (separately for each sector of equipment) will make delivered energy decline rather significantly. Demand management may further enhance the elasticity of electricity use. The cost of the assumed efficiency increases is far below the cost of producing the equivalent amounts of energy by any new technology.

7.2 Primary energy supply implications

The next step is to put together a supply scenario capable of delivering the prescribed quantities of energy to the end users. The scenarios are based on the Energy-21 action plan (66) as default, but includes considerations of the two scenario assumptions regarding efficiency improvements and the success of hydrogen technologies, and further extrapolates the system change away from fossil sources towards renewable ones to the year 2060, in order to assure consistency between short-term and long-term development. Figure 12 shows an estimate of the time needed to introduce or increase the contributions of renewable energy components in the Danish energy system. Wind power can be expanded at least at the rate of recent installations (off-shore). Biofuels (such as biodiesel, methanol or ethanol) will be the preferred use of agricultural and silvicultural waste material, rather than the combustion uses of today (they are included under "other", where at the end of the period one finds small contributions from sources such as solar and geothermal energy). Hydrogen as an intermediate energy carrier (and storage medium) comes in more slowly, in accordance with the technology readiness assessment made above. The data of Figure 12 should be considered as very preliminary, as the full project of analysing the 50 year transition or the snapshot scenarios has not yet been carried out.

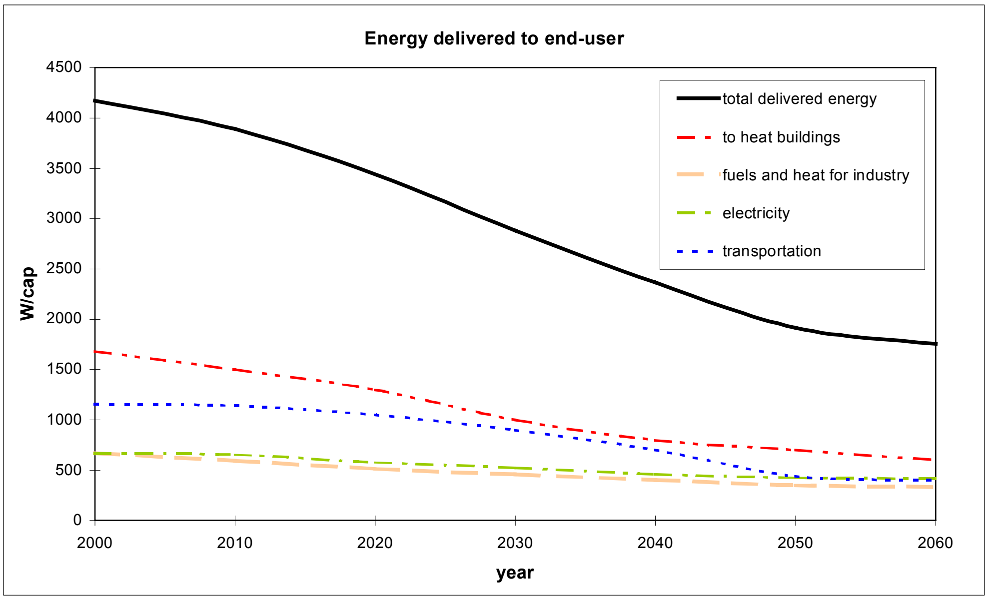

Figure 11. Scenario assumptions on the development of energy delivered to the end user.

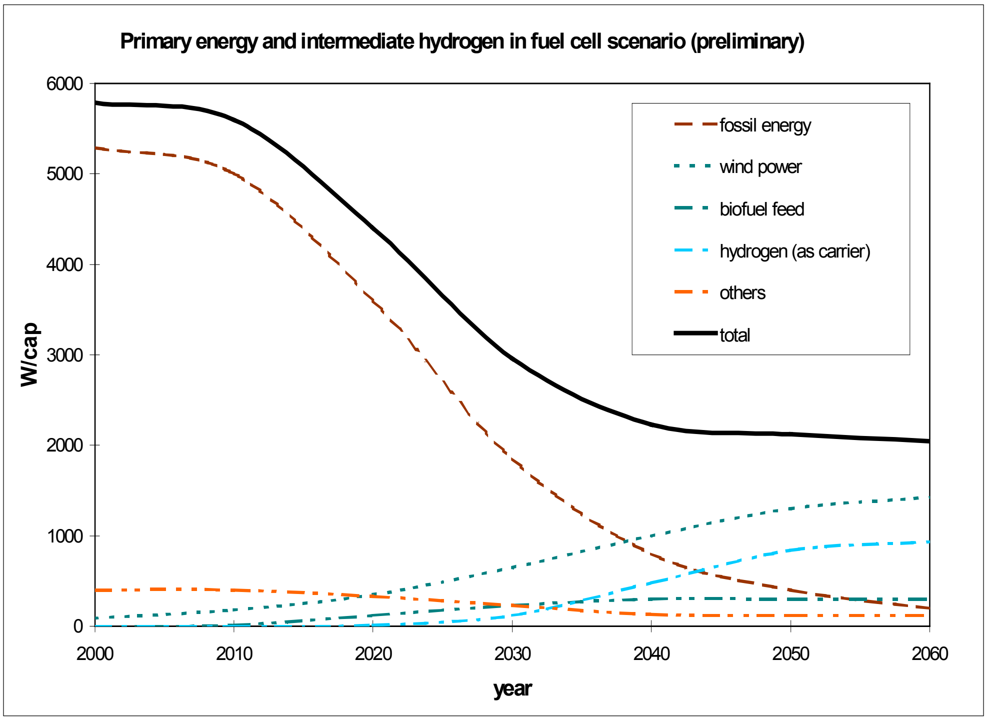

Figure 12. Estimated time development of efficiency improvements and introduction of new renewable energy sources while phasing out fossil resources, in response to assumed technology readiness and inertia for the optimistic fuel cell development scenario. The fossil decline is estimated on the basis of being able to satisfy the delivered-energy requirements of Figure 11, and it is coincidental if it agrees with the scenario of fossil phase out considered in section 1. Wind energy is by 2030 almost certainly going to exceed the 37% penetration in electricity supply envisaged by Energy-21 (66).

The update of the scenario work in (29) will require a major effort, particularly for describing the transition period where both the existing fossil system and the emerging renewable energy system are co-existing, due to the many constraints imposed by the structure of the old system (particularly those of power-heat co-production). No attempt will be made here of guessing the outcome of such work. However, for the end-point of the transition, where only renewable energy systems are in use, it is easier to make a rough sketch of the energy flows of the system.

The task consists in taking the end-use energy (Figure 10) and the energy delivered to the end-user (Figure 11) and work backwards through energy conversion steps to arrive at the primary energy inputs required.

7.3 The fuel cell scenario 2060

For the scenario where fuel cell development is assumed to have been successful in marketing durable fuel cells at an affordable price, both for automotive uses and for stationary uses in centralised or decentralised installations, the energy flow diagram ("Sankey diagram") may look as shown in Figure 13. Biofuels are assumed to be exploited on the basis of available waste (from agriculture and forestry) and used in specific sectors of transportation, such as freight transport. The rest (some 75% of the total transportation demand) is covered by vehicle fuel cells. Electricity is mainly from wind power, leading to some 50% having to go through the processes of hydrogen production, storage and regeneration of power in fuel cells, in order to cope with the variability of the primary production. Including losses, this allows a level of wind power exploitation similar to that of the previous report (29) to satisfy not only demand for transportation energy and direct electricity use, but also industrial process heat at higher temperatures that cannot be covered directly by hydrogen (with smaller losses), but also some low-temperature heat, assuming heat pumps to be used for maximum efficiency. The amount of such heat production covers the needs not covered by waste heat from the conversion processes through (already existing) district heating lines. The total primary energy requirement is 1756 W/cap (the Danish population assumed to be unchanged between now and 2060), plus 286 W/cap of environmental heat for the heat pumps. The fuel cell scenario is used as the end-point for the development in primary energy over time shown as Figure 12.

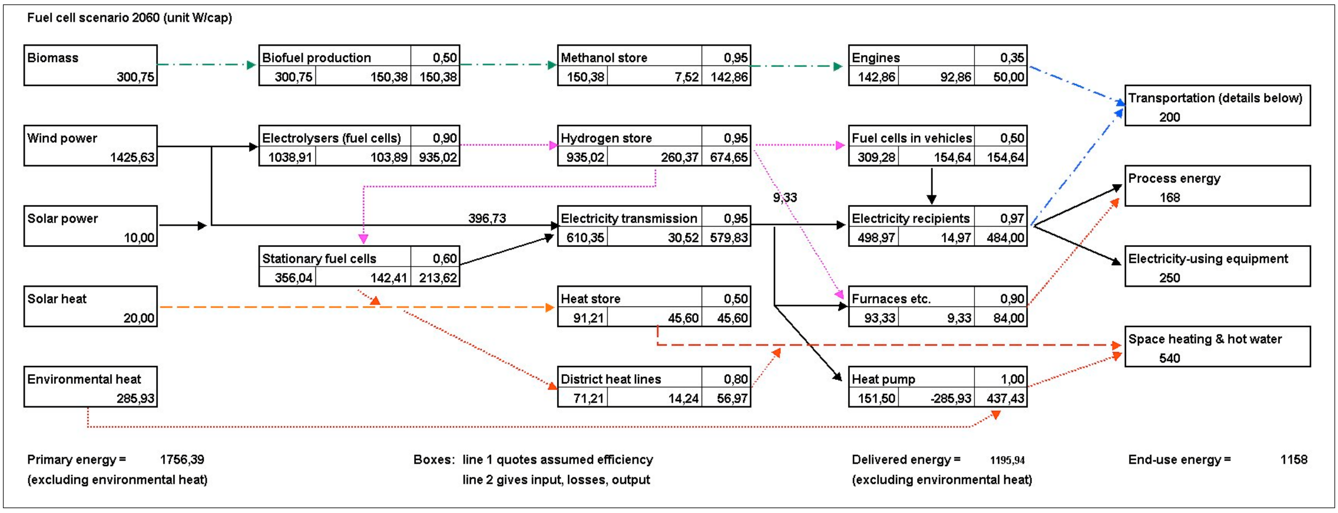

Figure 13. Danish 2060 scenario based on successful development of fuel cell technology.

7.4 The hydrogen storage scenario 2060

If the fuel cell development does not reach the anticipated cost or technical performance goals, hydrogen may still serve as a storable intermediate fuel in order to cope with the intermittency of renewable energy sources such as wind. The use of biofuels in the transportation sector is in this scenario, shown in Figure 14, increased to its estimated maximum level, and the remaining transportation energy demand (25%) is covered by electricity (trains, electric vehicles, the latter used mostly in urban areas). Due to the losses in the hydrogen storage cycle, where electrolysers could be fuel cell based (if the electrolyser cell development is more successful than the power cell development), but do not have to, and where gas turbines are used to regenerate electric power, there is nearly the same requirement for wind power production, in addition to the increased use of biofuels. Hence, the total primary energy supply must be 2317 W/cap plus 152 W/cap environmental heat. In other words, this less efficient supply chain requires 32% more primary energy than the fuel cell scenario.

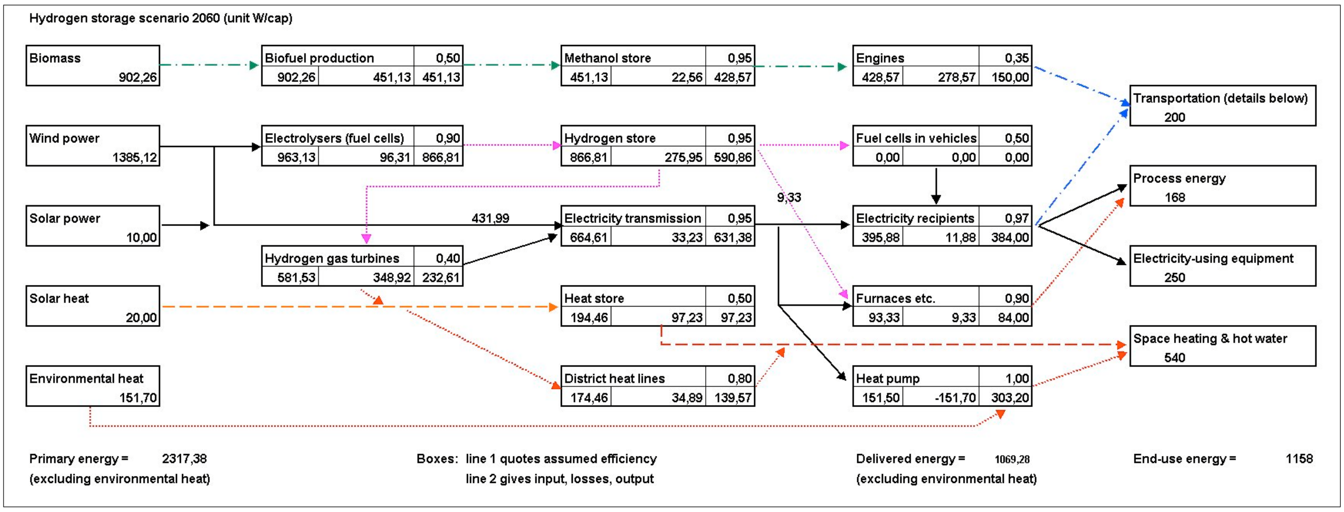

Figure 14. Danish 2060 scenario based on use of hydrogen storage without fuel cells.

8 Danish areas of strength and criteria for prioritis-ing action proposals

The recommendations made in section 9 take departure in the reports of refs. 58-61, but assess them in a coherent way, trying to avoid often sizeable variations in assumptions and attitudes of the stake-holders in each technology area. Criteria include global requirements and expectations, because Denmark is part of an intertwined international economic system with implications for many decisions in the energy area. Furthermore, the availability of Danish skills either in the areas considered, or in related areas that may be used or developed in a hydrogen context, are crucial for recommending public injection of funding. Areas related to hydrogen development where Denmark is strong include the following:

8.1 Basic research

The fundamental quantum chemistry issues of surface processes, and related experimental work, is in Denmark pursued by

• RUC Institute 2 Energy and Environment Group
• DTU Department of Physics Centre for Atomic-scale Physics
• AUC Institute of Physics
• AU Institute of Physics & Astronomy

In an international perspective, the work of these research groups is at the highest rank.

8.2 Applied research

• Materials research, SOFC processes: Risø Materials Science
• Intermediate temperature fuel cells: DTU Dept. Chemistry Structural Chemistry Group
• Biomass-based hydrogen (gasification, ethanol): Risø Plant Products Program, and others
• Life-cycle analysis of energy systems: RUC Institute 2 Energy and Environment Group
• Scenario and implementation analysis of energy systems: RUC Institute 2 Energy and Environment Group, Risø Systems Analysis Group

Similar competence is present in many parts of the world, but the Danish standing is of high rank.

8.3 Industrial development

• PEM fuel cells and DMFCs: IRD (including applied research)
• SOFC: Haldor Topsøe
• Gas infrastructure: DGC

• Fermentation routes to hydrogen: DTU, KVL and others

In most of these areas, the Danish players are small in an international context, but not necessarily inferior in a technical sense.

8.4 Industrial production

• PEM fuel cell systems: APC
• Catalysts, conventional large steam reformers: Haldor Topsøe
• Compressed underground gas storage: DONG

Also here, Danish players are small on an international scale, except for the conventional steam reforming technology.

8.5 System assembly

Several additional companies have qualifications and may step into the area, when the basic technology is seen as ready.

8.6 Other competence

A number of additional institutions and enterprises have shown interest in hydrogen. When funding and niche markets are available, there may be a development of new centres of competence.

The second factor in selecting areas for support is the timeframe, over which results can be expected. The previous sections have argued, that hydrogen R&D is highly important now, in order to secure a transition to a renewable energy system, which may take a half century to complete, but which is already in progress, with a wind power penetration that has been quicker and less expensive than expected 5 years ago (66). Yet each proposed activity must have clear milestones, that have to be reached as a condition for supporting the following phase.

9 Recommendations for research, development and market stimulation

The following recommendations are directed at efforts over the next 5 years and assume proper evaluation of progress. The types of effort suggested are denoted as *(b, a)* for desirable support of basic and applied science efforts and as *(d, p)* for industrial development and early-phase production/market-related support.

9.1 Hydrogen production

During a transition phase towards the introduction of hydrogen as an energy carrier in the Danish energy system, production of hydrogen from fossil fuels may be relevant for an accelerated upstart. Conventionally produced hydrogen can readily fill this need, and the only area that may need industrial development is small scale reforming of natural gas for stationary applications. Several international companies are already in this market, and tax-payer support for Danish manufacturers would not seem very appropriate. Exceptions may be novel concepts integrating reforming of natural gas or biofuels with fuel cells, but again there are many foreign competitors already far into this kind of development.

As mentioned in section 2.1, recent advances make reversible PEM fuel cells interesting for decentralised hydrogen production (a possibility already suggested in ref. 29). It may not be too late for Danish developers to join in this technology, which would be a natural interest for anyone working with PEM fuel cells. It is also a technology that it would be useful to demonstrate under Danish conditions, as part of an early public awareness and initial market stimulation effort, also if some of the hardware must be imported.

Conventional alkaline electrolysers are not included as an area requiring support, although there might be some industrial development potential in increasing efficiency for the smaller units aimed at decentralised operation. In short the recommendations are:

• *Small reformers (d p); reversible PEM cells (b a d); reversible or just reverse operation SOFCs (b a).*

9.2 Hydrogen storage

Hydrogen storage technologies of interest for Denmark include geological cavern storage of compressed gas and small stores for decentralised stationary or mobile uses, with high safety and energy density, and with sufficient rates of charging and discharging for the proposed applications (metal and advanced hydrides, carbon surfaces, etc.). Further development of existing technologies such as flask compressed hydrogen to higher pressures or liquefied hydrogen is considered less relevant for Denmark.

- *Salt intrusion and aquifer hydrogen storage (b a d); hydride and related storage technologies (b a d).*

9.3 Transport applications

Denmark possesses skills for taking part in the further development of PEM fuel cells for various types of vehicles (with close relations to work directed at stationary uses), including basic research optimising and catalyst development efforts, as well as systems items such as on-board control systems. At the moment no fuel cell collaboration with the auto industry is ongoing. Interesting special research areas include use of reversible PEM cells in vehicles (for electrolyser operation when parked near buildings) and development of intermediate-temperature cells.

- *PEM fuel cells (b a d p, cf. stationary applications below); Control systems (d p); intermediate-temperature acid (PEM-like) cells (b a).*

9.4 Stationary applications

For stationary application, including combined power and heat production as well as reversed operation, areas of interest comprises PEM fuel cells of high durability and reliable operation in the 1-25 kW size range (some of which may be the same as used in the transportation sector), as well as large SOFCs for power plant use in connection with central hydrogen stores. Smaller size SOFCs, initially for use with fossil fuels may also be of interest where the high temperatures can be accepted, as may the intermediate-temperature fuel cells mentioned above.

- *PEM fuel cells and systems as above (b a d p); CPH systems (d p); SOFCs and systems (b a d p).*

9.5 Other areas

It is judged that Denmark does not have the skills for a significant contribution to portable fuel cell systems. However, other system combinations may be forthcoming, in addition to the UPSs and building-integrated CPH-units mentioned above. As regards infrastructure, hydrogen filling stations have already been developed in several other countries and Denmark is not seen as favoured with particular skills in this area. However, in designing transmission and distribution systems, the earlier debate on making our natural gas lines "hydrogen-ready" (which did not happen) shows that skills in this area do exist.

A general need is to create viable science and development environments with sufficient base financing to be sustainable also during periods of less available project funds. This is seen as particularly required in the general area of vehicle research (as contrasted to the existing transportation institutions charged with evaluating traffic and road planning).

General system and scenario work is a hallmark of the Danish scientific tradition and a very relevant type of investigation in connection with the introduction of hydrogen in the energy supply system. Studies of this type, including life-cycle assessments, should be pursued throughout the preparatory and implementation phases.

- *Scenario studies and environmental (LCA) work (b a); Establish permanent basic research units in areas such as sustainable transportation and renewable energy systems (b a); New types of system integration (b a d).*

Demonstration programs and later market stimulation (fixed-duration initiation support if public money) are particularly relevant for the items in section 9.3 and 9.4, with products aimed at the general consumer market. Enterprises may contribute further market-preparing activities. Regarding work on norms and standards in the hydrogen area it is suggested that the current practice of adopting German norms and standards is sufficient, as these are seen as adequate for Danish industry. International collaboration is seen as highly desirable, especially in the research phases. The European industry platform has in a recent draft report suggested priorities for hydrogen R&D very similar to ours (69).

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